

2025/9/17

10th East Asian Numerical
Astrophysics Meeting

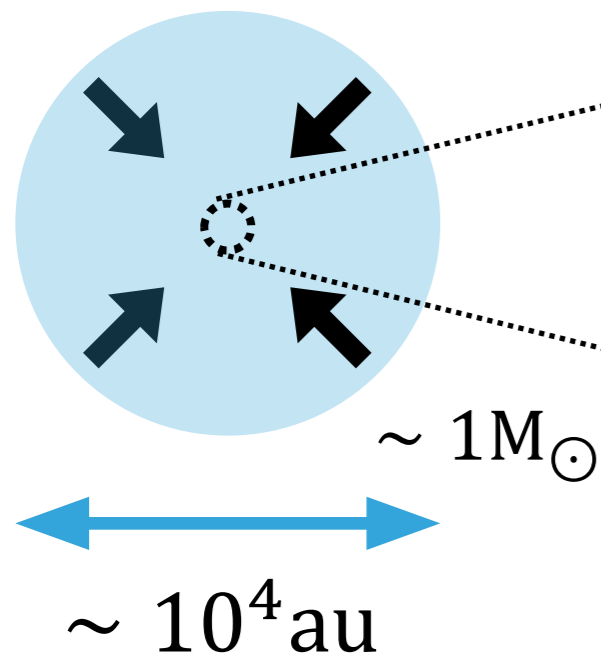
1

Formation and Early Evolution of Protoplanetary Disks under Nonuniform Cosmic-Ray Ionization

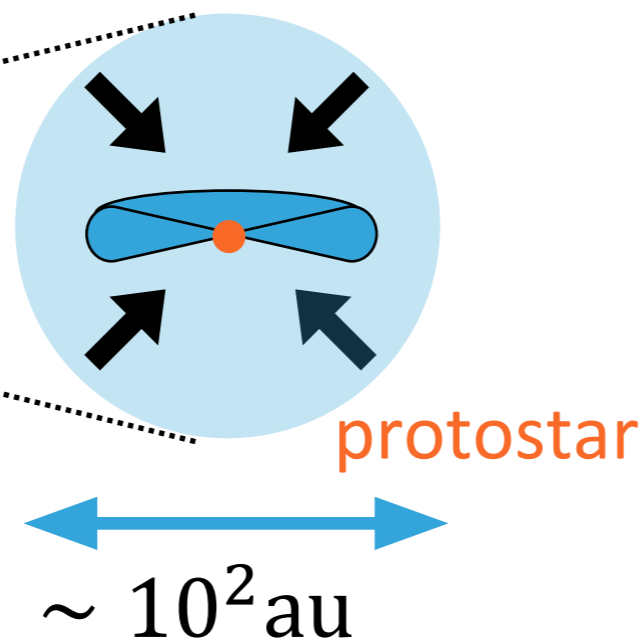
Tohoku University
Erika Nishio

Collaborators : Kengo Tomida, Yuki Kudoh, Shigeo S. Kimura

molecular cloud
core



protoplanetary disk



Through a disk,
surrounding gas
accretes to the protostar

A Gas clump collapses
by gravity
→ Star formation

- How much is accretion rate?
 ℓ_z is extracted from gas
→ gas accretes to protostar

- What determines disk size?

$$R_K = \ell_K^2 / GM$$

ℓ_z is large → disk is big

M is large → disk is small

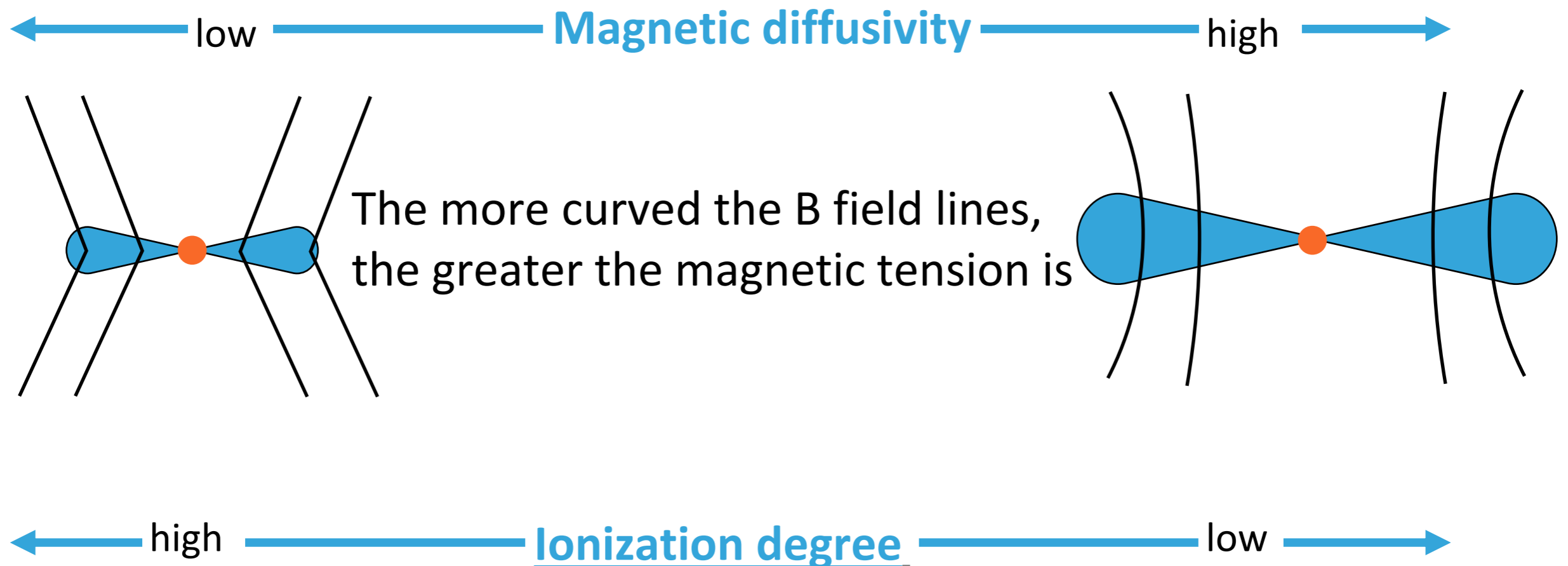
Angular momentum transport is important!

$$\partial_t(\rho r v_\phi) + \nabla \cdot r[\rho v_\phi \mathbf{v} + \left(P + \frac{B^2}{8\pi} - \frac{g^2}{8\pi G} \right) \mathbf{e}_\phi \left[-\frac{B_\phi}{4\pi} \mathbf{B} + \frac{g_\phi}{4\pi G} \mathbf{g} \right]] = 0$$

gravitational torque

magnetic braking

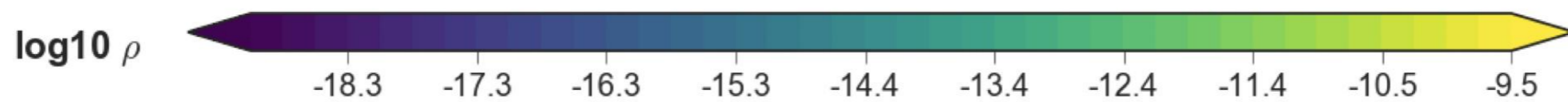
A disk receives magnetic braking → The disk size becomes smaller



Main ionization source in star formation region is **cosmic rays (CR)**

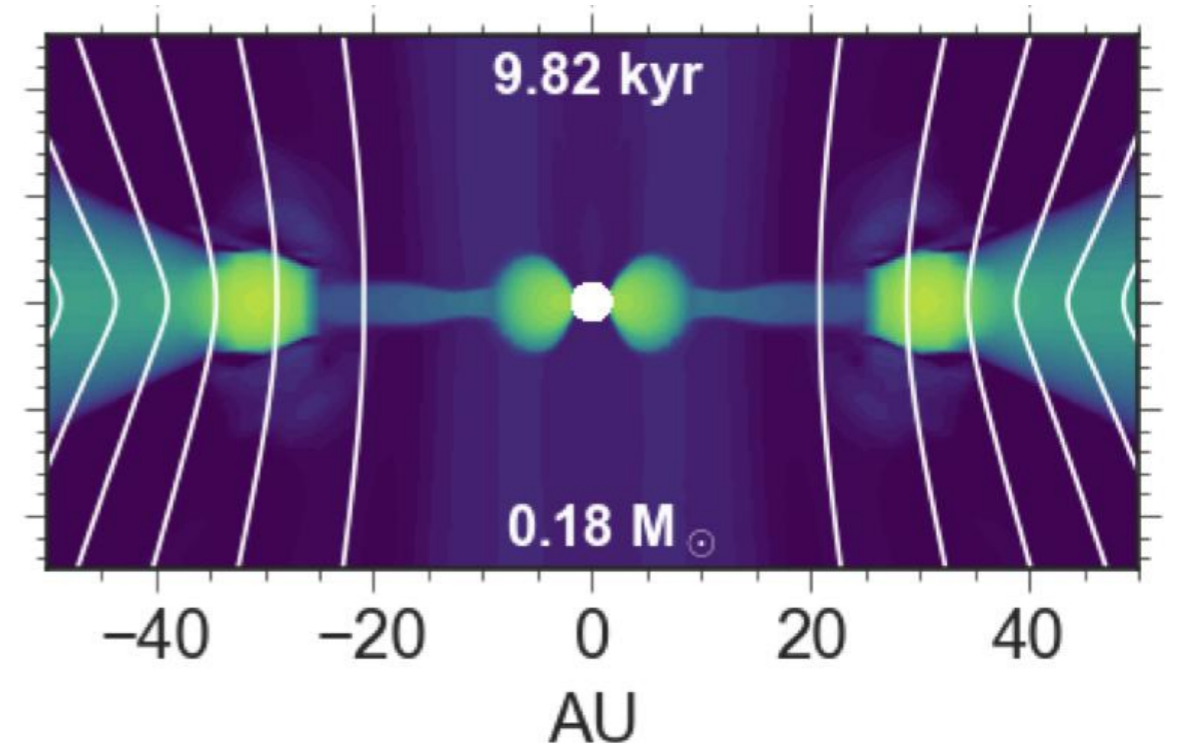
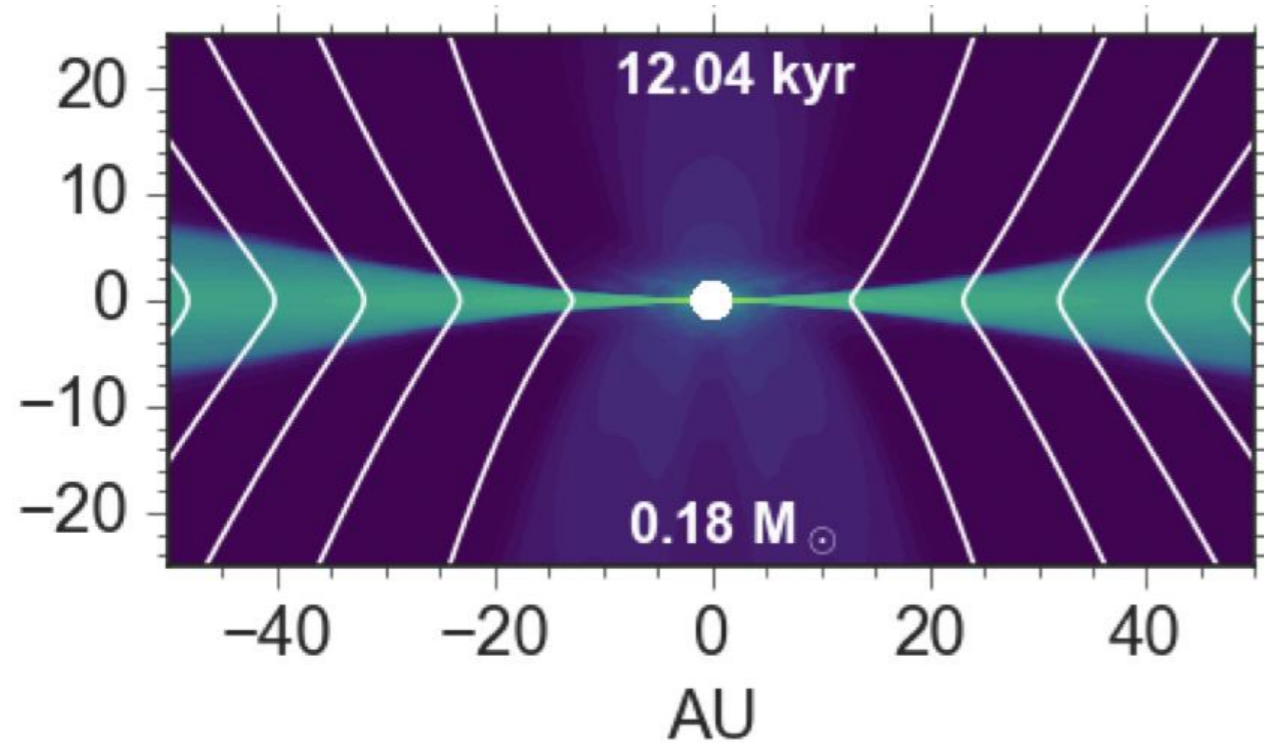
Effect of ionization rate on disk evolution

Ionization rate $\zeta [s^{-1}]$: Number of hits by CRs to a H_2 per second
($\sim \sigma v_p n_c$ typical value : $10^{-16} s^{-1} - 10^{-18} s^{-1}$)



$$\zeta = 10^{-16} s^{-1}$$

$$\zeta = 10^{-17} s^{-1}$$

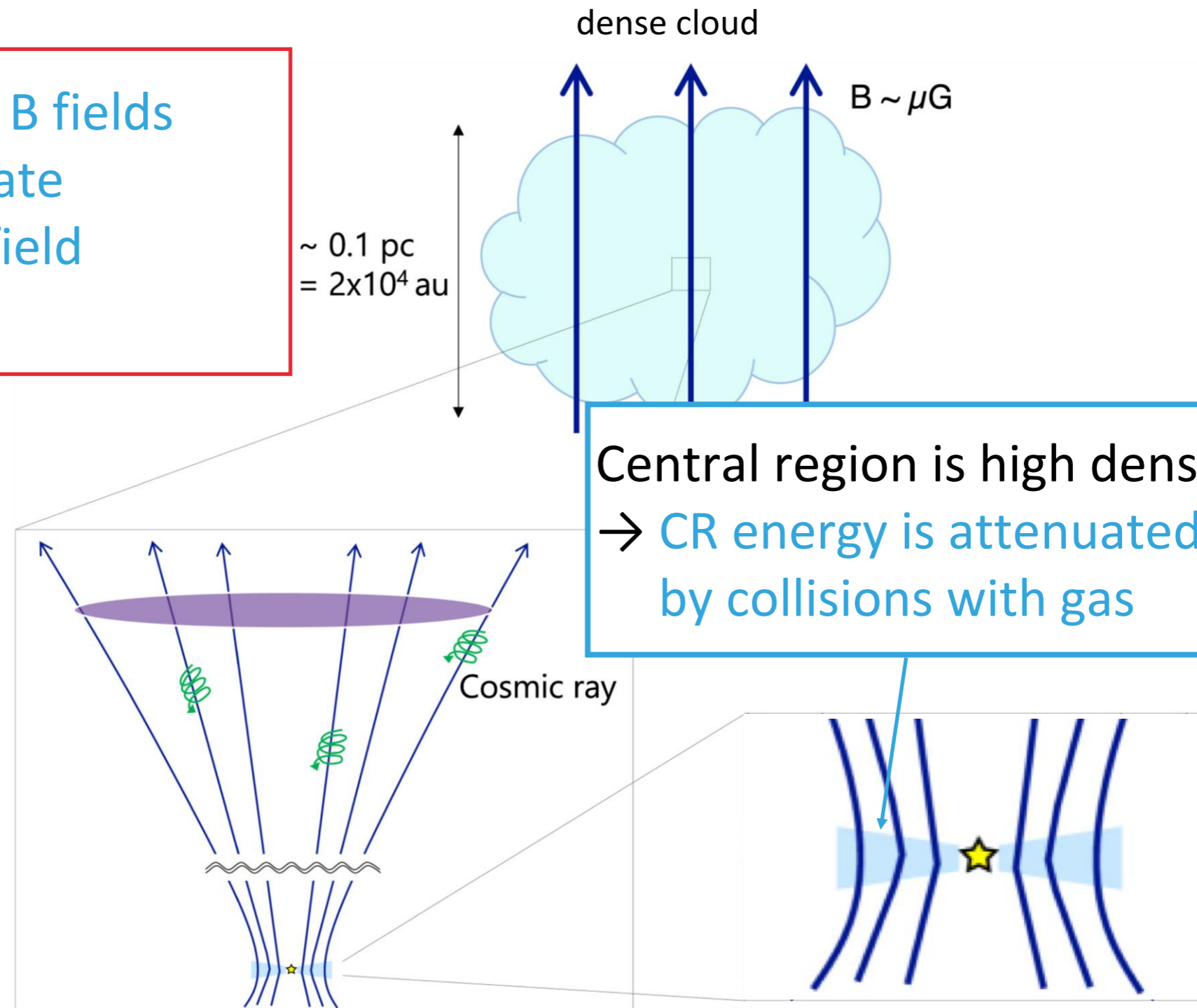


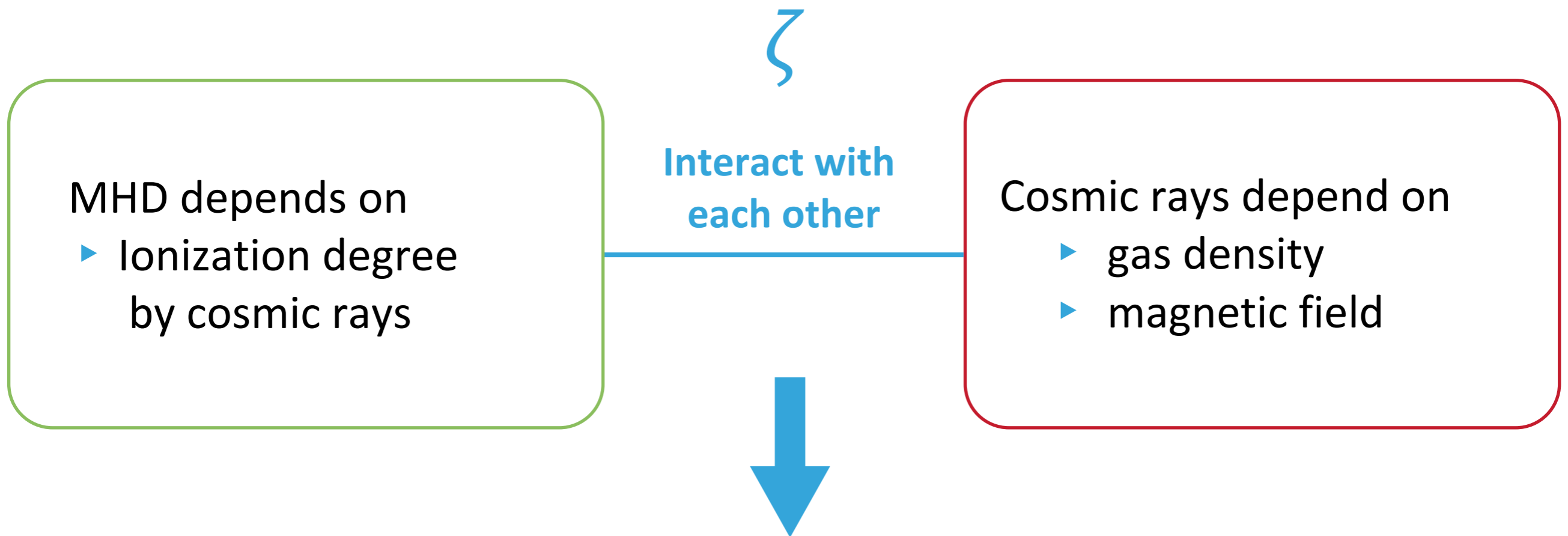
Kuffmeier et al.2020

Change in cosmic ray ionization alters disk evolution

Energy density of CRs depends on the distribution of gas & B field lines

CR propagates along B fields
→ Many CRs propagate in areas where B field lines converge





To understand how cosmic ray ionization affects protoplanetary disks, we have to consider **the mutual interaction of CRs and gas**

→ Calculate { **Cosmic ray transport equation**
Non-ideal MHD equation } **together**

Non-ideal MHD & CR transport equations

Non-ideal MHD

Code : [Athena++](#) (Stone et al.2020)

● Temperature evolution (Zhao+ 2018)

$$T = \begin{cases} T_0 + 1.5 \frac{\rho}{10^{-13}} & \text{for } \rho < 10^{-12} \\ (T_0 + 15) \left(\frac{\rho}{10^{-12}} \right)^{0.6} & \text{for } 10^{-12} \leq \rho \leq 10^{-11} \\ 10^{0.6} (T_0 + 15) \left(\frac{\rho}{10^{-11}} \right)^{0.44} & \text{for } 10^{-11} < \rho \end{cases}$$

● Induction equation of non-ideal MHD

$$\begin{aligned} \frac{\partial \mathbf{B}}{\partial t} - \nabla \times (\mathbf{v} \times \mathbf{B}) \\ = \nabla \times \left[\eta_{\Omega} \nabla \times \mathbf{B} + \frac{\eta_{AD}}{|\mathbf{B}|^2} \mathbf{B} \times (\nabla \times \mathbf{B} \times \mathbf{B}) \right] \end{aligned}$$

Hall effect is ignored (for simplicity)

Size of dust : $0.1 \mu m$

dust-to-gas ratio : 0.01

η_{Ω}, η_{AD} are calculated from ρ, B, T, ζ

Okuzumi 2009

Cosmic ray transport

Diffusion + single bin approximation

$$\begin{aligned} \frac{\partial}{\partial t} e_c + \nabla \cdot (e_c \mathbf{v}) - p_c \nabla \cdot \mathbf{v} \rightarrow \text{Ignore} \\ = \nabla \cdot (\mathbb{K} \nabla e_c) - \Lambda_{\text{coll}} n_{\text{H}_2} e_c \end{aligned}$$

Smaller than other terms

$$\mathbb{K} \equiv K_{ij} = K_{\perp} \delta_{ij} + (K_{\parallel} - K_{\perp}) n_i n_j$$

$$K_{\parallel} = 100 K_{\perp}, \quad n_i = B_i / |\mathbf{B}|, \quad p_c = e_c / 3$$

Diffuse in direction along B

Ionization rate : $\zeta = \zeta_p + \zeta_{\text{SLR}}$

- $\zeta_p \equiv \Lambda_{\text{coll}} e_c / 50 \text{ eV}$

CRs propagating from interstellar space

- $\zeta_{\text{SLR}} = 10^{-18} \text{ s}^{-1}$

CRs produced by the decay of radioactive elements in star-forming regions

Including the effects of CRs through ζ in the simulation of star formation

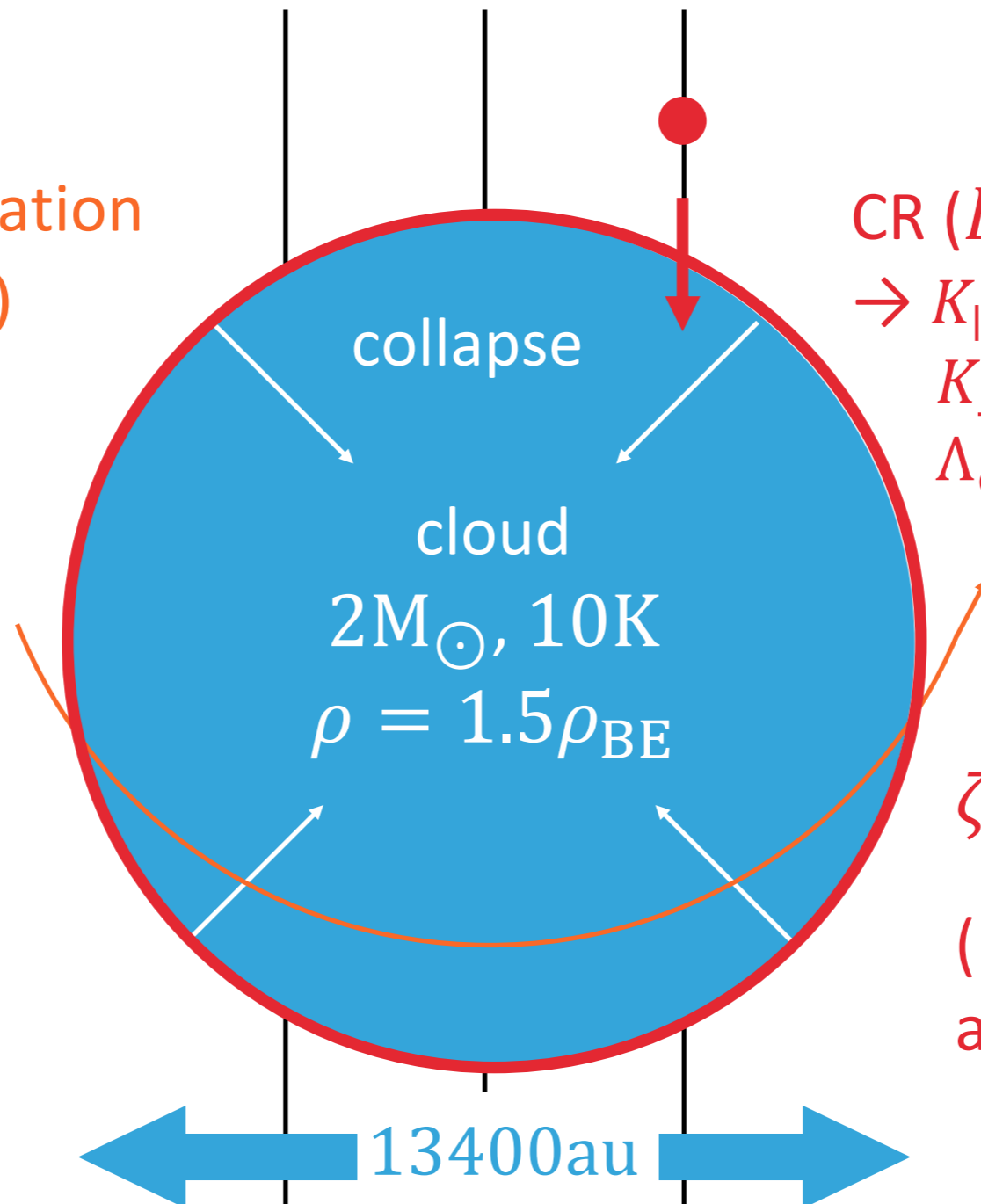
Ω : Solid body rotation
($\Omega t_{\text{ff}} = 0.3$)

CR ($E_k = 30\text{MeV}$)

$\rightarrow K_{\parallel} = 3.9 \times 10^{26} \text{cm}^2 \text{s}^{-1}$

$K_{\perp} = 3.9 \times 10^{24} \text{cm}^2 \text{s}^{-1}$

$\Lambda_{\text{coll}} = 3.3 \times 10^{-14} \text{cm}^3 \text{s}^{-1}$



B_z : uniform
($\mu = 2$)

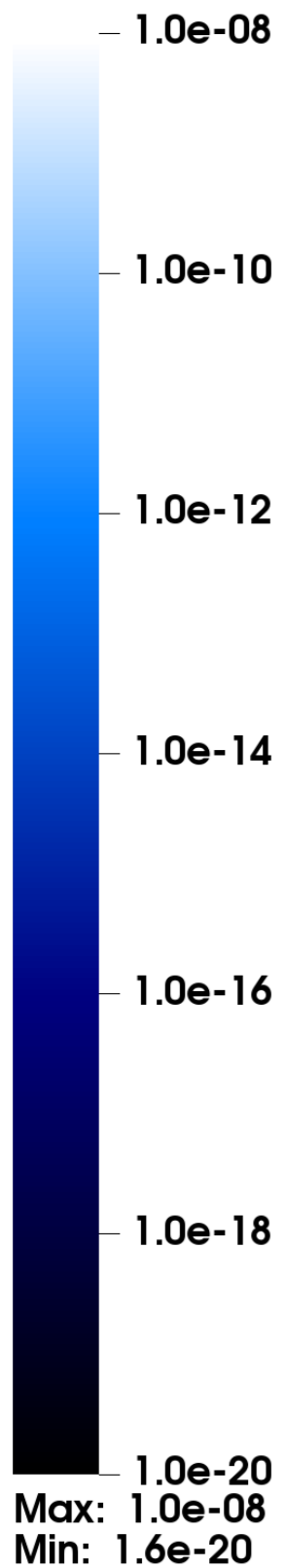
$\zeta_{\text{ex}} = 10^{-16} \text{s}^{-1}$

(Ionization rate
at interstellar space)

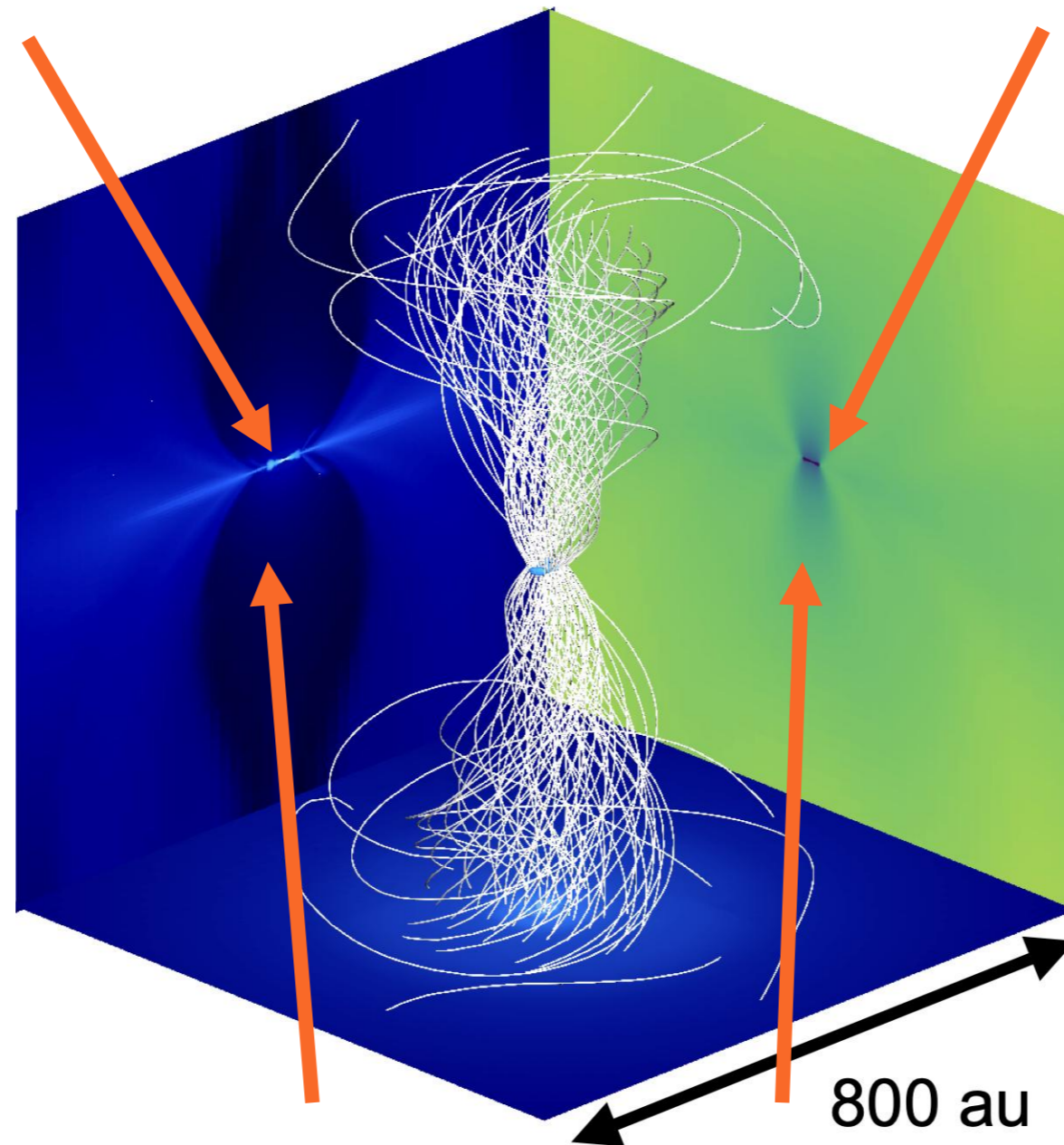
Model	DD	const
Ionization rate	considering CR transport	constant ionization rate

Density & CR ionization rate distribution

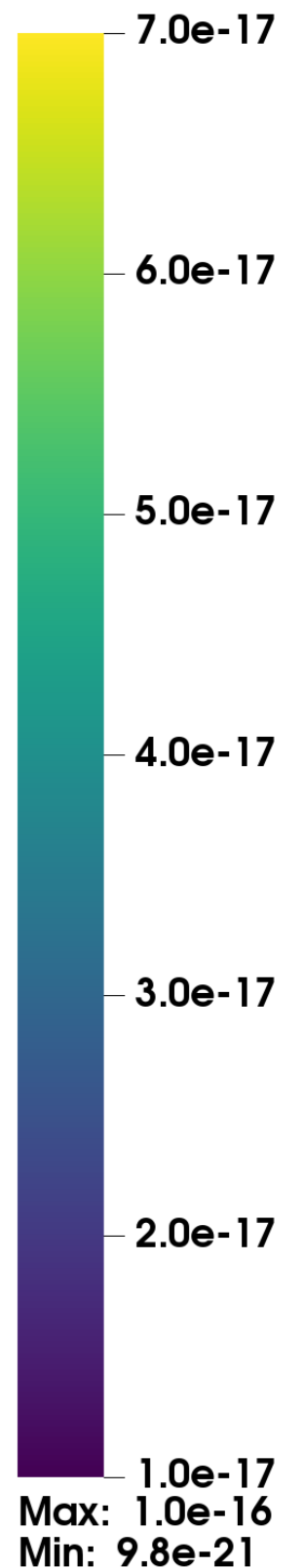
$\rho(\text{g/cm}^3)$



Central region is high density
→ CR energy is attenuated by collisions with gas
 ζ_p is attenuated by more than one order of magnitude

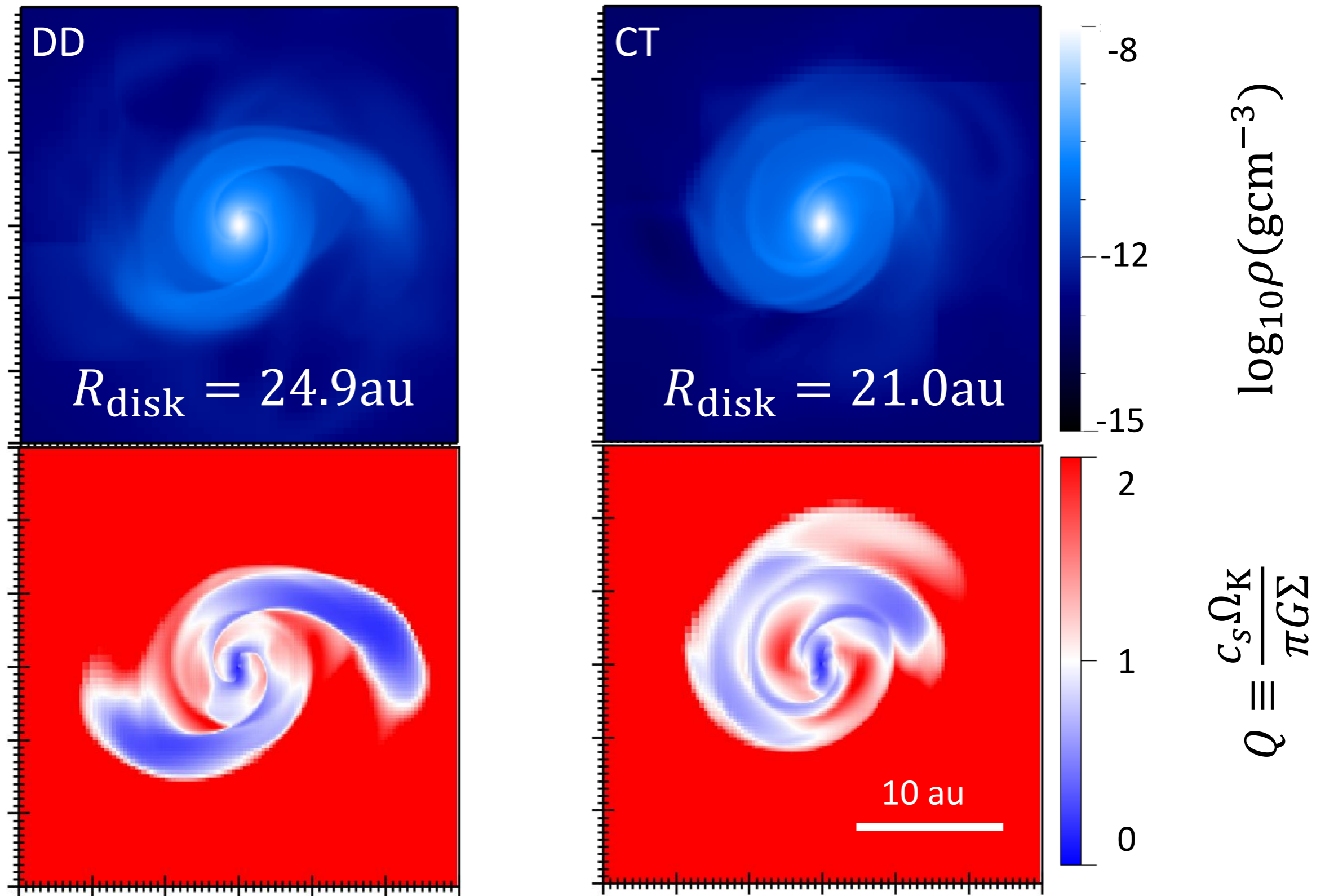


$\zeta_p(\text{s}^{-1})$



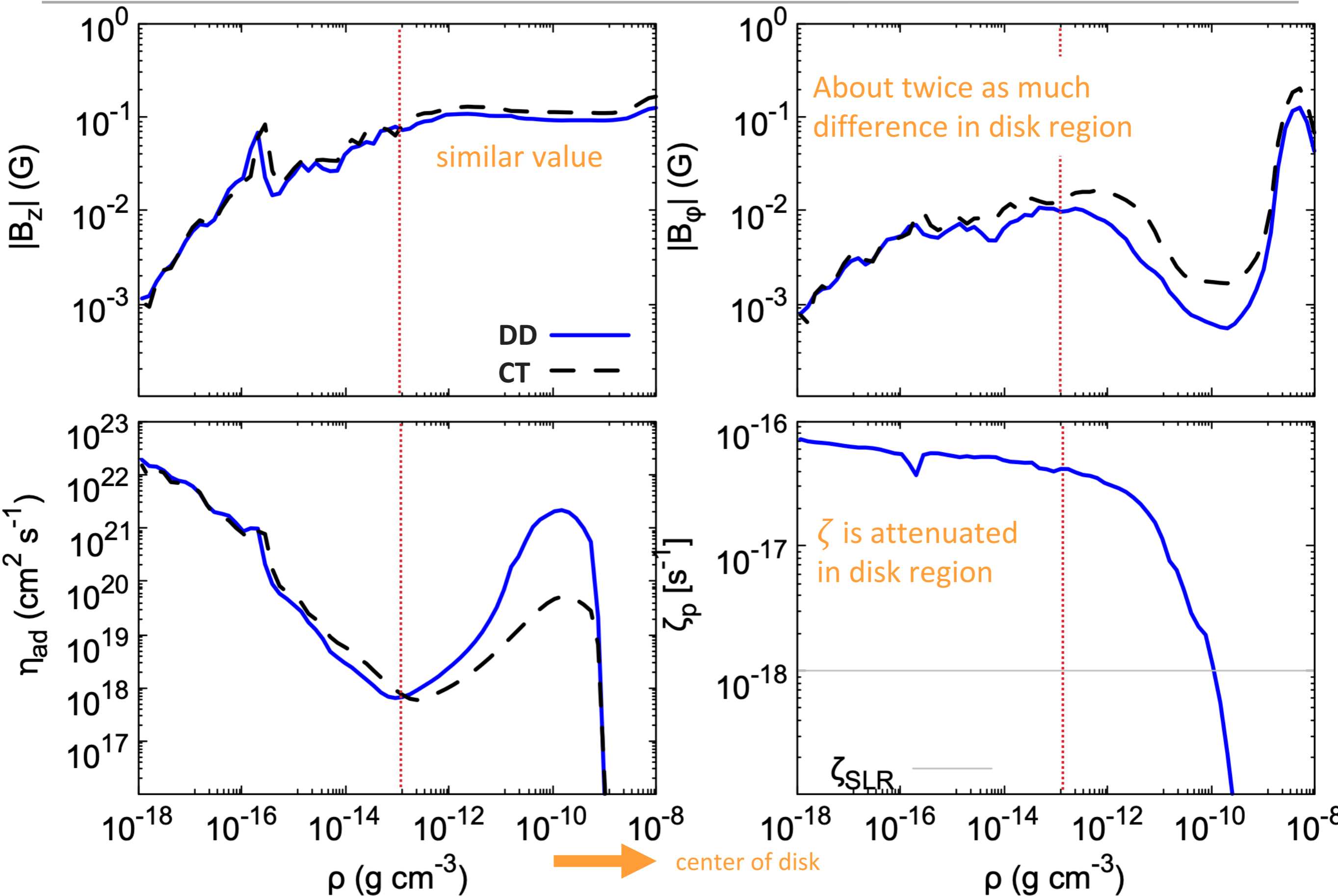
Outflow region is connected to the disk by B field lines
→ CRs flow into disk through B field lines & CR decrease

Comparison of disk

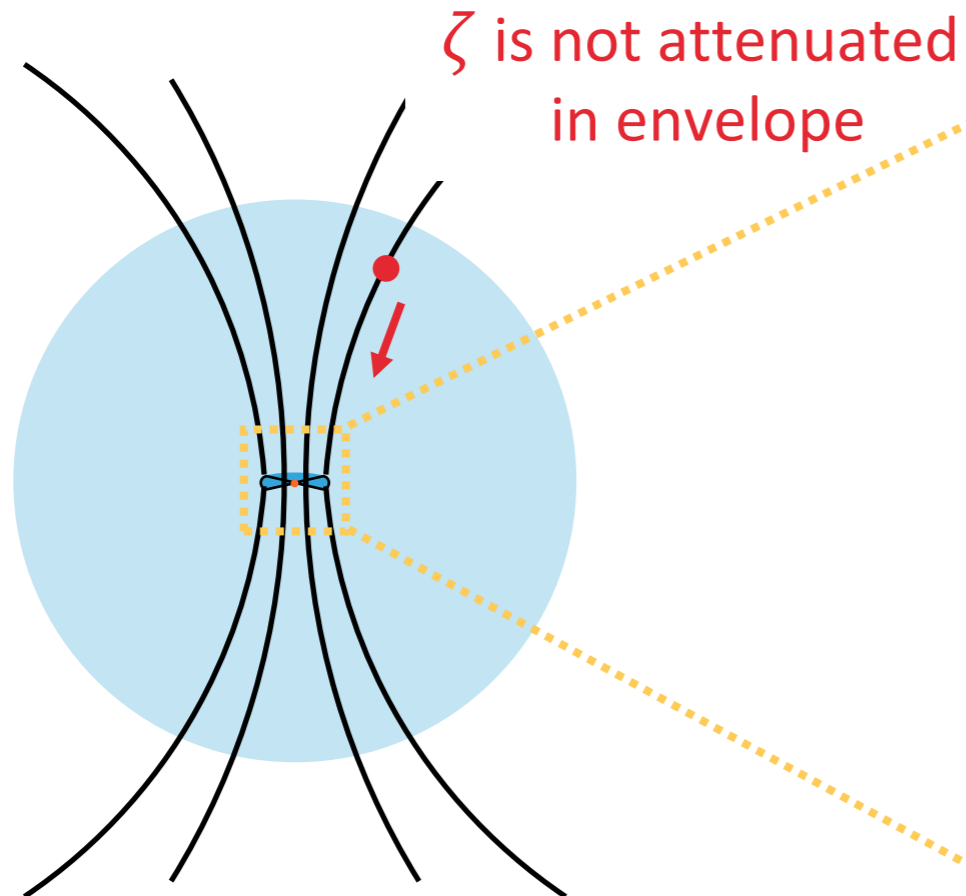


DD has more visible and extended spiral arms than CT

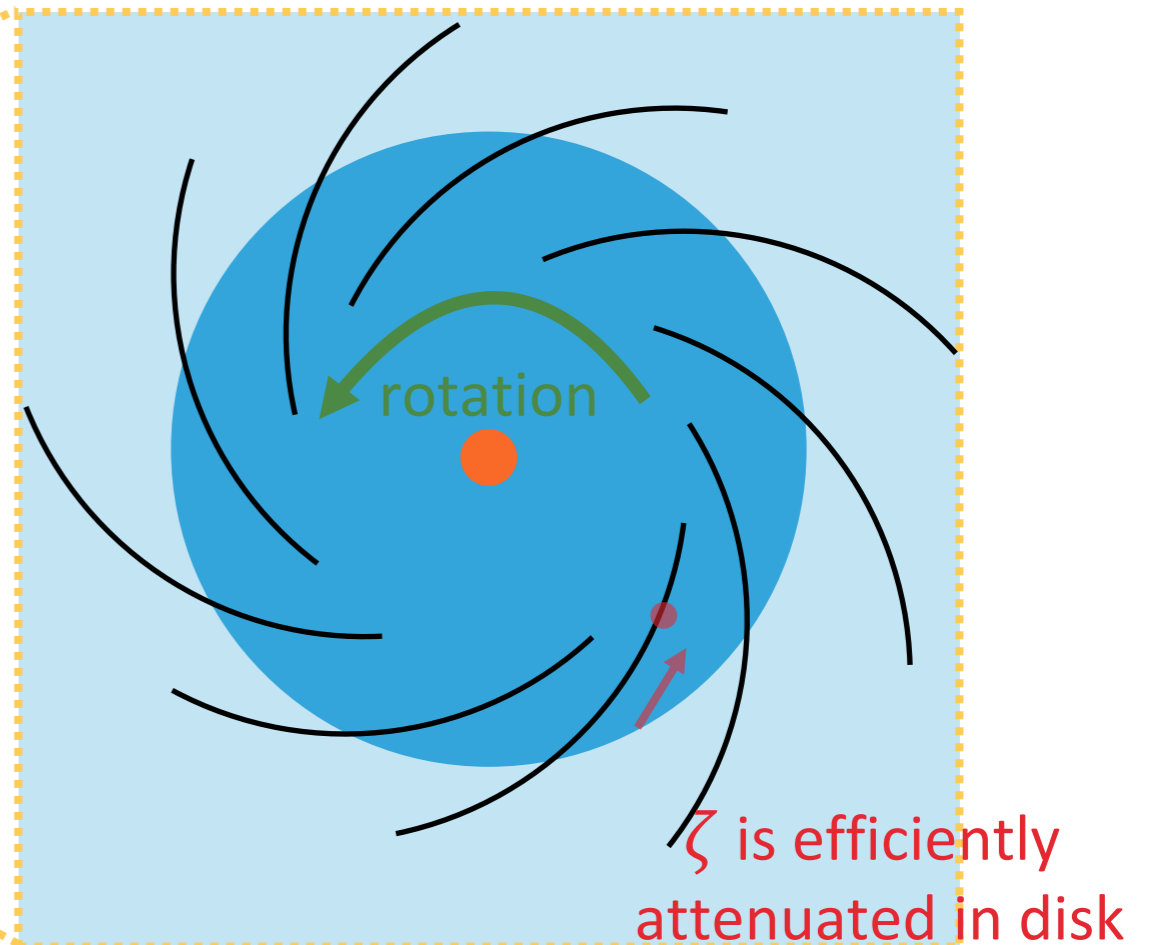
Magnetic field and ionization rate



What determines B_z ?



What determines B_ϕ ?



B_z is brought into disk
by gas accretion

→ Dependent on ζ environment
in star forming region

B_ϕ is amplified by differential
rotation in disk

→ Dependent on ζ in disk

▶ Method

We have investigated the evolution of protoplanetary disks in the early phase of star formation using a newly developed non-ideal MHD simulation code that incorporates cosmic ray transport.

▶ Result

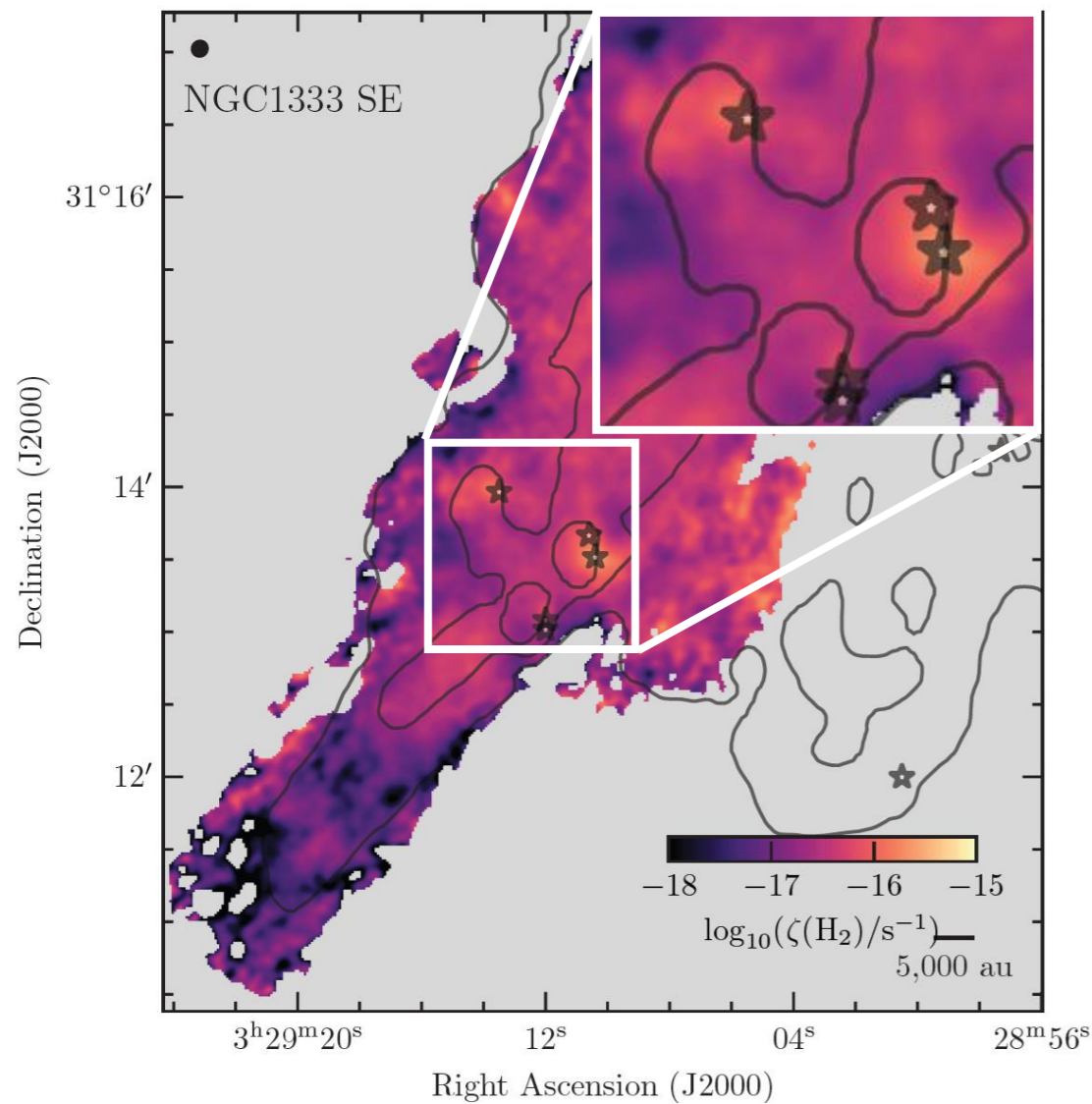
1. The value of the ionization rate in the disk is more than one order of magnitude smaller than the value in interstellar space.
2. DD has more visible and extended spiral arms than CT.
3. B_z is similar between the two models, but B_ϕ is twice as different. It is because ζ is efficiently attenuated in disk region and η_{AD} is higher in this region.

▶ Discussion

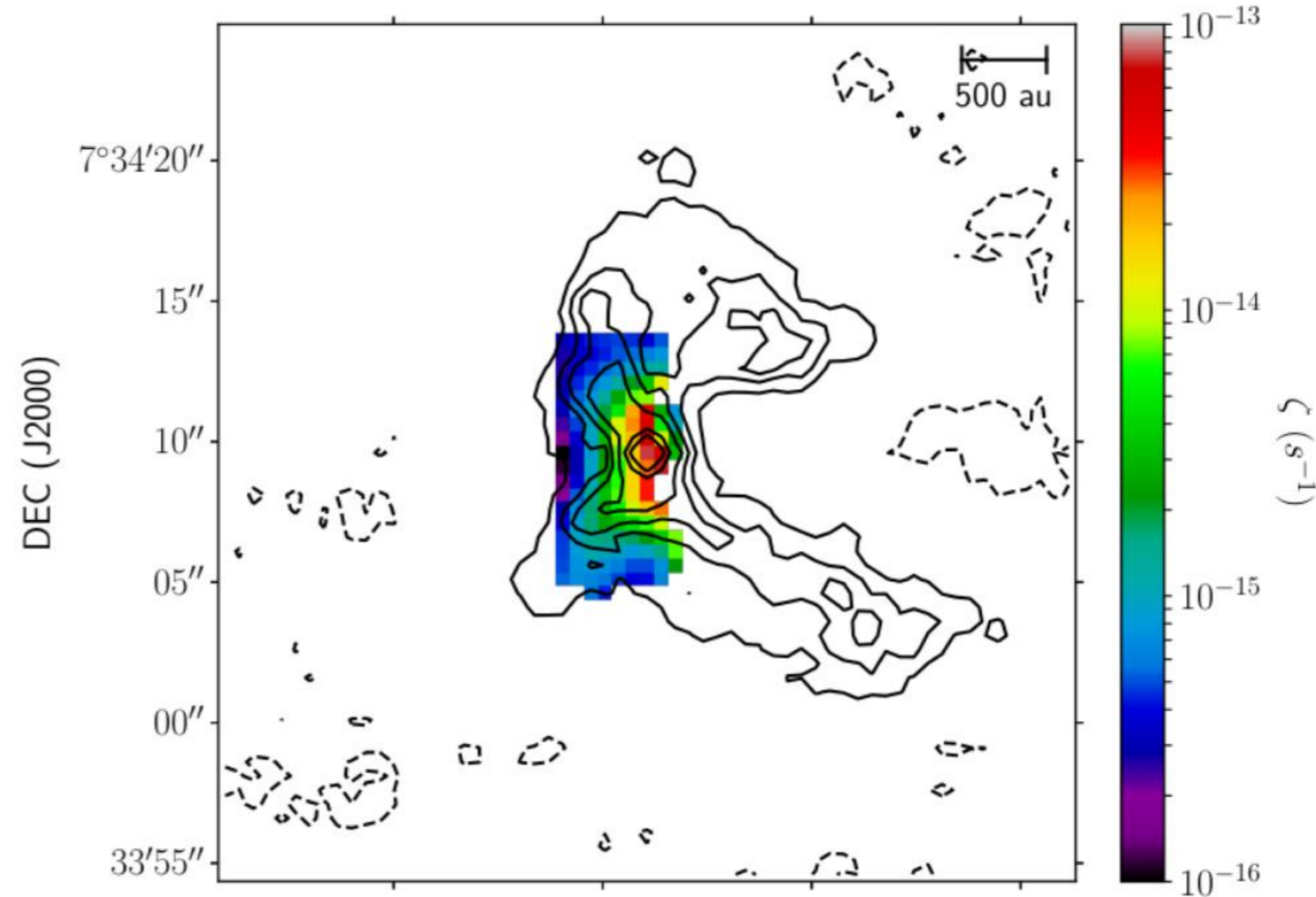
1. What determines the B_z in the disk depends on the ζ environment around the molecular cloud core.
2. What determines the B_ϕ in the disk are depends on the ζ distribution in disk.

Back up

Observation of ionization rate around protostar 15



NGC 1333 (Pineda et al. 2024)



Class-0 protostar B335 (Cabedo et al. 2023)

Typical value in star-forming region : $10^{-16} - 10^{-18} \text{s}^{-1}$



Recently observation : Ionization rates are high around star-forming regions
→ **Actual disk may be smaller** than disk considered with typical ionization rates

Used CR transport equation is $\frac{\partial}{\partial t} e_c = \nabla \cdot \left(\overleftrightarrow{K} \nabla e_c \right) - \Lambda_{\text{coll}} n_{\text{H}_2} e_c$

1. discretize using **implicit method**

(backward Euler method + central difference)

→ Stable regardless of timestep

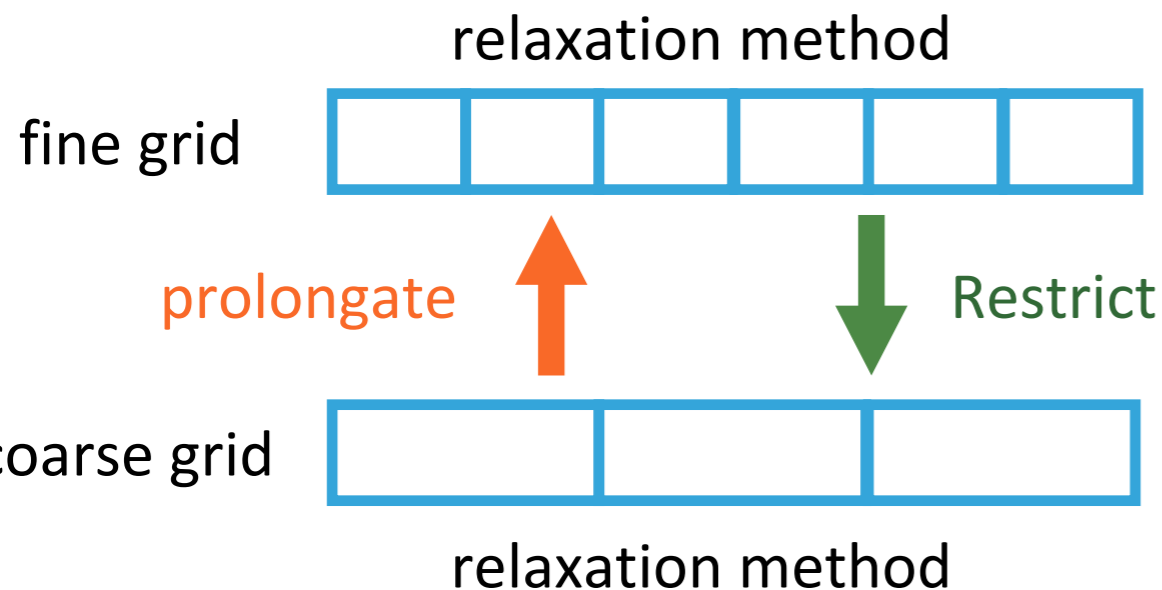
2. solve it using **full Multigrid method** (Based on Tomida & Stone 2023)

Timescale of diffusion eq is $\tau \sim L^2 / |D|$ (L : scale of system, D : diffusion coefficient)

Short wavelength residuals : damp quickly

Long wavelength residuals : damp slowly

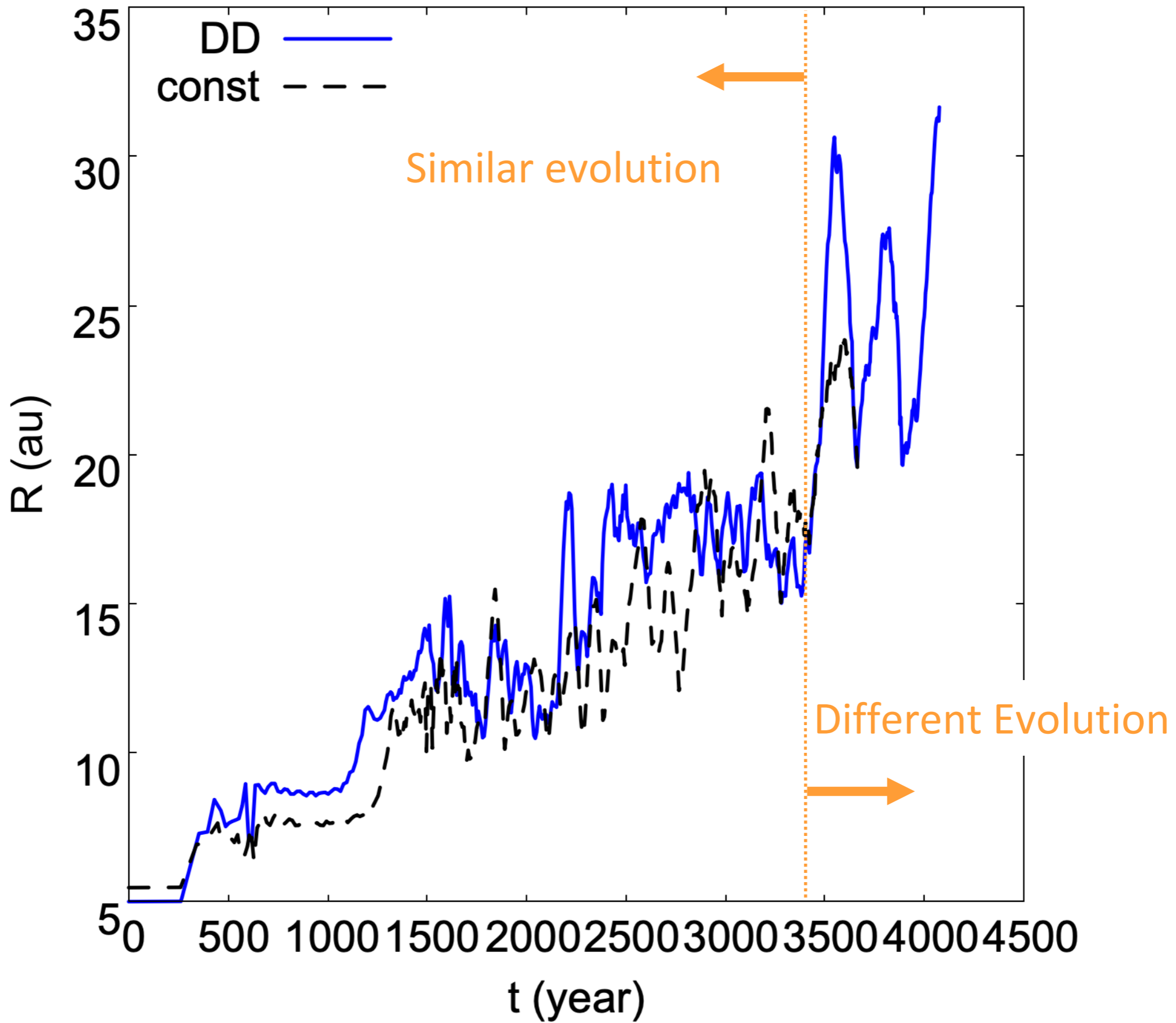
→ Long wavelength residuals can damp in fewer iterations **using coarse grids**



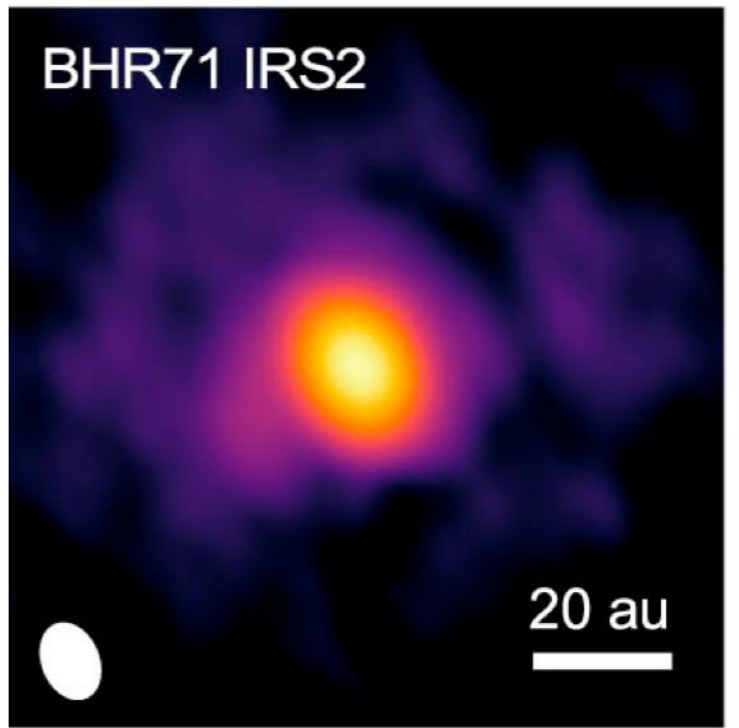
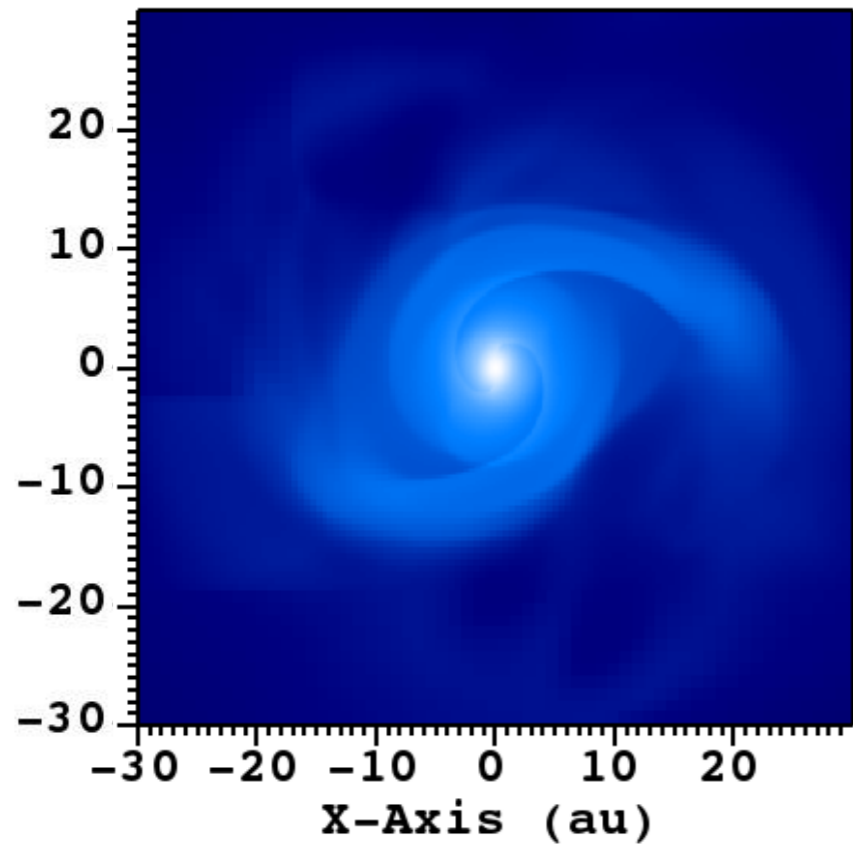
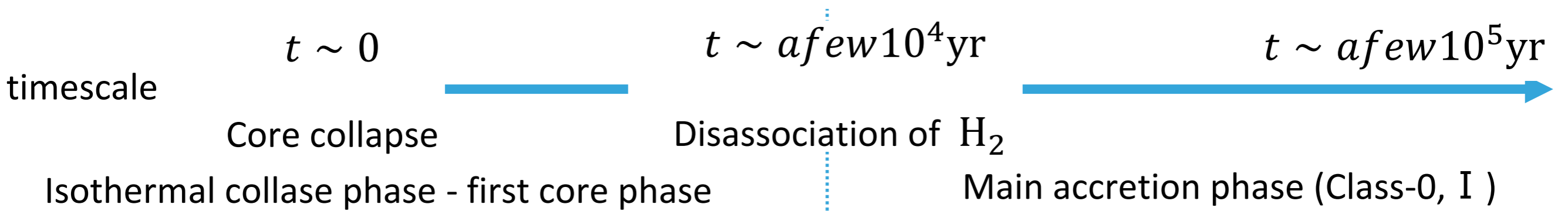
Multigrid method damps residuals of all the wavelengths coherently.

→ The number of iterations no longer depends on the original lattice spacing & it can be **significantly reduced**.

Time evolution of disk radii



Comparison with disk observation



(eDisk : Ohashi et al.2023)

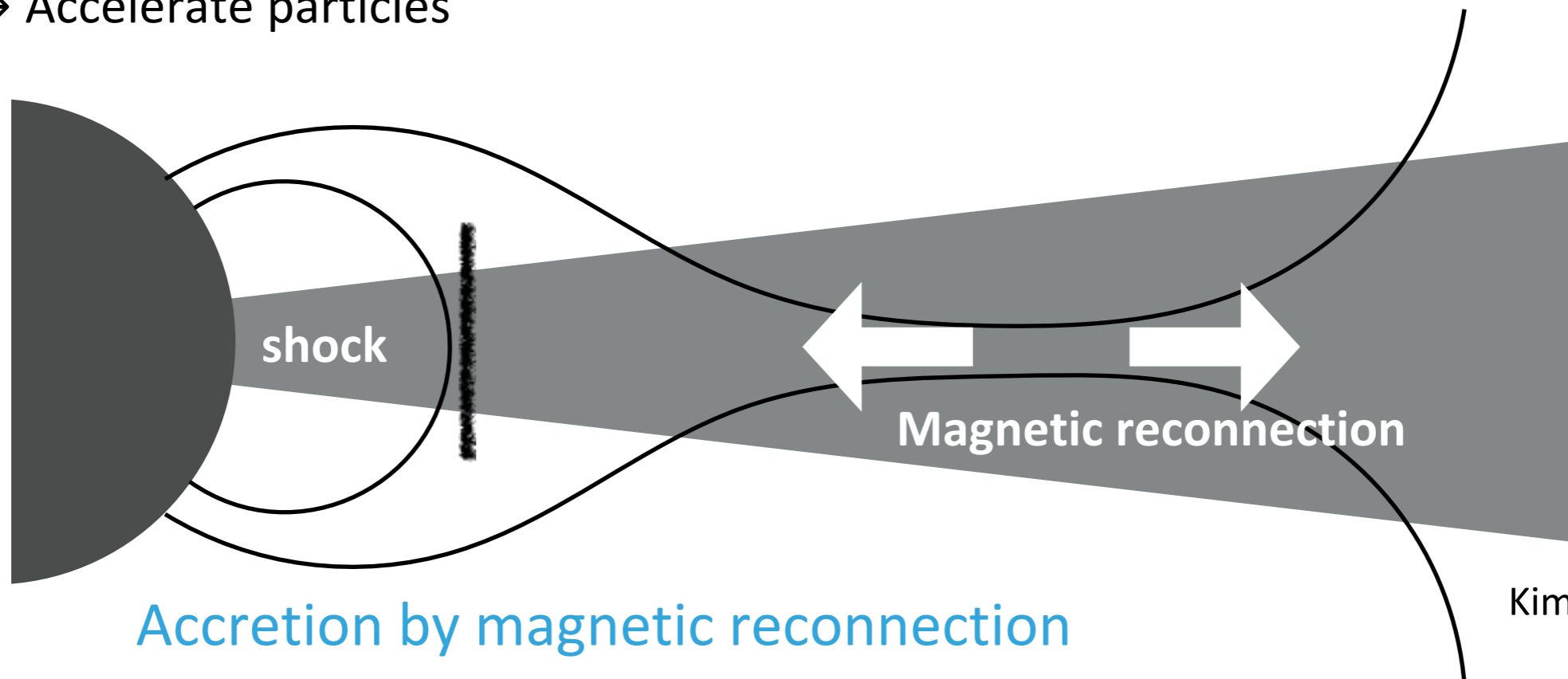
Incorporating the attenuation of CR makes it easier for spiral arms to form.

Spiral arms are not visible in observations

ability of physics that enhance angular momentum transport by the magnetic field, leading to the disappearance of spiral arms

Fermi accretion by shock in accretion flows

Shock is formed by collision of accretionary flow on surface of a protostar
→ Accelerate particles



Kimura et al. 2023

Accretion by magnetic reconnection

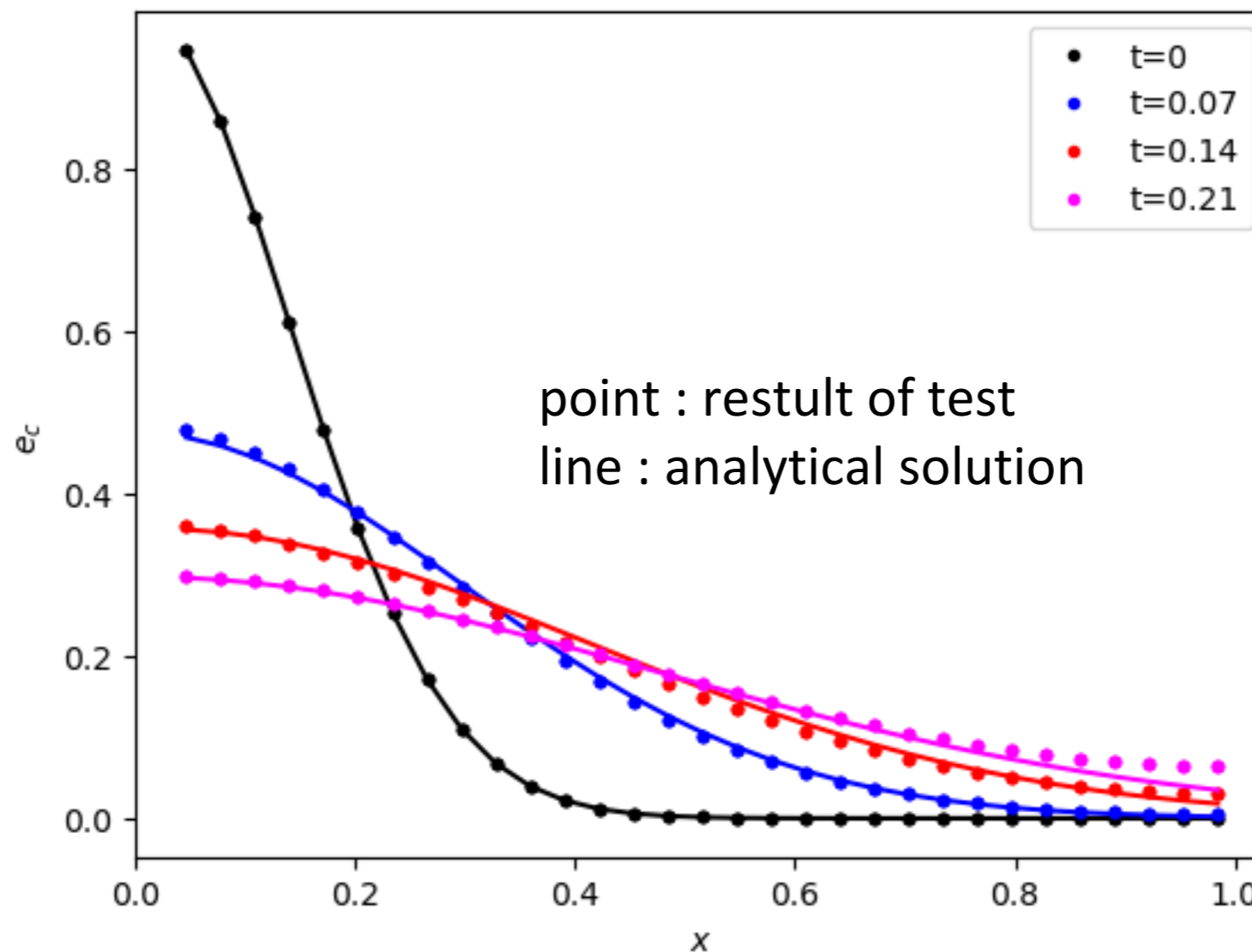
Jet generated by reconnection generates shock
→ Accelerate particles

CRs generated in star-forming region ionize disk
→ Magnetic diffusion can be smaller and
angular momentum transport due to the magnetic field can be larger

$$\frac{\partial e_c}{\partial t} + \nabla \cdot (e_c \mathbf{v}) = -p_c \nabla \cdot \mathbf{v} + \nabla \cdot (K \nabla e_c) - \Lambda_{\text{coll}} n_{\text{H}_2} e_c$$

Initial condition : $e_{\text{CR},0} = A \exp\left(-\frac{x^2}{r_0^2}\right)$

analytical solution : $e_{\text{CR}}(x, t) = A \sqrt{\frac{r_0^2}{r_0^2 + 4Kt}} \exp\left(-\frac{x^2}{r_0^2 + 4Kt}\right)$



$$\Sigma_0 = m_{\text{H}_2} \left(\frac{3m_{\text{H}_2} \Lambda_{\text{coll}}}{\rho K_{\parallel}} + \frac{\Lambda_{\text{coll}}^2}{v_p^2} \right)^{-1/2}$$

